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Visual and Cognitive Issues in the Design of Displays

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In order for a visual display to be useful, the human user must be able to see and understand what is displayed—allowing information to become knowledge. It follows, then, that for a display to be of maximum utility, characteristics of human vision and cognition must be considered in the design process. This report contains both general design guidelines as well as specific information that can be useful to the display designer wishing to optimize a display for the user. Because human vision and cognition are such complex topics, references to in-depth treatments of specific issues are provided. Therefore, the report serves a dual purpose: to acquaint the display designer with basic human issues in the design of visual displays, and to serve as a pointer to classical and contemporary research into human visual perception and cognition.

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1. Introduction

It is strange, but true, that with the current explosion of information technology, a common term like *display* can lead to misunderstanding. For some, it refers to a piece of hardware (e.g., a computer monitor). For others, a display is the visual stimuli generated by a device.* Either usage of the word *display* is appropriate as long as the intended meaning is clear. To avoid this semantic pitfall, I use the term *display* herein to refer to the visual stimuli generated by a device that are intended to convey meaning to the viewer.

As display designers develop new information systems, they need to be aware that these systems, once fielded, will be operated by people with varying levels of expertise and under conditions that can be quite different from those experienced by the designer. Thus, the best system performance will not be achieved solely by the push of technology. Successful information systems will result from the thoughtful integration of enabling technologies with empirically derived principles of human perception and cognition. The purpose of this report is to acquaint the display designer with some of the very basic issues that relate to how people use (or misuse) visual information.

What, then, are the characteristics of a "good" display? This simple question has an unfortunately elusive answer. It is a bit like asking, "What should one look for in acquiring a good stereo speaker?" The response usually takes the form of more questions. How is the speaker going to be used? What will the acoustic environment be like? What are the capabilities of the amplifier that will drive the speaker? And so on. There does not (yet) exist a single, straightforward list of engineering specifications that can answer all cases of the question, "How do I optimize my display?" However, there are guidelines that can be useful. Some guidelines are specific, in which case they may not apply across a broad spectrum of display usage. Other guidelines are more general, in which case they may be of limited assistance in answering highly specific questions about particular displays. I address both types in the sections that follow, beginning with general principles.

2. General Guidelines for Display Design

2.1 Promote Situation Awareness

Displays used in tactical or command and control applications should aid the user in developing good situation awareness (SA). SA is one of those terms that everyone seems to understand, intuitively, and yet no single

* *To complicate matters, the information displayed on a computer monitor is often referred to as the human-computer interface (HCI), or user interface, even though the HCI is actually composed of both the information output from the device and the method(s) by which the user interacts with the system.*

definition is widely accepted. Endsley's definition (1995, p 65) has probably come the closest: "The perception of elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future." In this context, SA is a *process*, not a product. Another way of thinking about SA is to consider the questions we often ask ourselves (even if subconsciously): "What is happening? How did this come to be? What will happen next?" Clearly, SA is driven by the dynamics of a situation, is highly context dependent, and is time sensitive in that it normally improves with exposure to the situation. It is a combination of ecological information (our expectations and what we sense about the world around us), synthetic (machine-generated) information, and the goals we are trying to accomplish.

I mention SA first, because I hope it will provide an overall perspective that encourages the reader to view users not as passive information receivers, but as people seeking (often desperately) meaning about the world around them in order to decide what to do next. Many of the following guidelines address issues important in designing displays that aid the user in developing and maintaining SA. The interested reader may wish to learn more by consulting Endsley (1995), Rasmussen and Vicente (1989), and Woods (1995).

2.2 Support User's Mental Model of System

The more the display supports the user's mental model of the system being monitored or controlled, the better. Every user constructs an internal model for mentally visualizing the system represented by the display. For example, the nuclear power plant control room operator must visualize the physical layout and processes of the facility in order to make correct decisions regarding its regulation. A display suite that is configured to support the operator's internal model will result in superior performance, both in terms of decision times and error rates (Wickens, 1984).

2.3 Use Analog Representations

People are essentially analog thinkers. Accordingly, visual displays should present information in a relative, rather than absolute, format whenever possible. This is not to suggest that all, or even any, absolute displays should be eliminated. The point is simply that information displayed in a relative format allows for the integration of complex, multidimensional stimuli in a way that encourages parallel processing of the displayed information. Thus analog representations can provide substantial savings of cognitive resources. These savings accrue from reduced memory and computational loads, because the analog display acts as external memory and facilitates memory referencing and retrieval (Walrath, 1989; Woods, 1986).

2.4 Include Historical Information

The recent history of a system should be readily available to its user. The large, positive correlation between adjacent regions in time and space has not gone unnoticed by mankind, and is at the root of our tendency to see events causally. There is no question that people tend to reach decisions about the near future based on events in the near past (Moray, 1980). A display that does not provide recent history for important elements requires the user to rely on short-term memory. This will inevitably lead to errors, because people cannot maintain perfectly accurate short-term memory recall even under the best of circumstances. Violating this principle contributed to the 1988 downing of Iran Air Flight 655 by the USS *Vincennes*, resulting in the loss of the aircraft and all 290 passengers aboard. This tragic loss of life might have been prevented if the radar display provided target altitude history to its operator who, after a brief distraction, wrongly concluded that the aircraft was in a descending (hostile) flight path.

2.5 Exploit Proximity

When two sources of information must be combined, mentally, they should be displayed in close physical proximity. Conversely, if two sources of information are unrelated, and therefore processed separately, it may be beneficial to separate them in display space. Known as the *proximity compatibility principle* (Wickens, 1992a), this principle leads to fewer cognitive demands on the user as a result of having to search for one piece of information while keeping another in short-term memory. Wickens (1992b) argues that this *information access cost* can be reduced via several methods, such as (1) configuring the display of related information sources to appear as separate dimensions of a single object; (2) combining different sources of information into higher dimensional representations (e.g., showing a single point on a three-dimensional graph as opposed to using two planar graphs); and (3) using color to group display elements.

2.6 Make Mode Changes Clear

Advances in hardware, software, digital communications, and data base access have provided the computer scientist with, effectively, limitless amounts of information that can be displayed in countless ways. As a result, the trend has been to develop displays with multiple modes because there is often too much information to be shown in a single format. Sophisticated systems may even switch modes automatically, in response to autonomous sensor data. Not surprisingly, this has been followed by increased user errors resulting either from misidentifying the current mode or from initiating a control input that, while allowable in some modes, is inappropriate for the current one. Some examples of mode errors that have occurred in commercial aviation, and their catastrophic consequences, are reported by Sarter and Woods (1995). Designing the display to promote viewer mode awareness is essential, especially for highly automated systems.

2.7 Be Visually Consistent

Display elements that are consulted regularly should be placed in the same location regardless of display mode. For example, if weapons control orders are shown in the lower right corner of the display, then they should appear in the same screen location in all other tactical display modes. This *consistency* principle reduces the cost of information access by relieving the operator of having to search the screen to find an often referenced data element. Consistency has one drawback, however: a loss of flexibility that results from the need to reserve screen areas across all modes. As more information elements stake claims to specific areas of display real estate, both display space and design flexibility diminish. The conflict between consistency and flexibility should be resolved early in the design process.

2.8 Maintain Visual Momentum

Multifunction displays often allow the user to view the same domain in more than one way. Cartographic displays are one obvious example. The transition from one view (or method of viewing) to another can result in the user "getting lost" in the information space. Preserving the correspondence between the display and the user's mental model of the domain, across different views, is referred to as "maintaining visual momentum" (Woods, 1984). Wickens (1992b) has suggested four methods of maintaining visual momentum:

Consistency. Discussed earlier, consistency refers to preserving properties of information elements across multiple display modes.

Graceful transitions. When a viewpoint is changed, it is advantageous to show the change occurring rather than to just switch from one to the other. For example, when opening a folder icon to display its contents, some personal computer operating systems show the folder rapidly growing (or zooming) in size, ultimately becoming a new window showing the items stored inside the folder. When this window is closed, it rapidly shrinks, becoming once again the folder icon. This dynamic visual transition helps the user maintain a mental model of what is happening, as well as where individual items can be found within the domain.

Display overlap. When the user changes from one display view to another, some prominent elements from the old view should be visible in the new view—providing the viewer a "landmark" with which to understand the relationship between the two views.

Global "big picture" displays. Another way to keep the user from getting lost in the domain is to reserve a small area on the display for a representation of the entire information space. The depiction should indicate from where, within this global space, the current display is taken. This is easy to imagine for a cartographic display. The global display would show a certain terrestrial area (e.g., the United States) with a smaller area highlighted to indicate what is being displayed on the rest of the screen (e.g., Montana). The

principle extends to other than cartographic displays, however, as illustrated by data base work done by Vicente and Williges (1988).

2.9 Consider User Expectations

A major tenet of cognitive psychology is that human perceptual processing is both *data driven* and *concept driven*. Data-driven processing is determined by the immediate stimulus information arriving from the outside world. Concept-driven processing is guided by information already stored in memory (e.g., prior knowledge based on experience and formal learning). Human visual perception involves the integration of data-driven processes (operating on stimulus energy) and concept-driven processes (imposing our expectations on our perception of reality). While it is not clear how expectations work downward to affect low-level visual processes, experimental results clearly indicate that they do (Coren and Ward, 1979). What we perceive visually is, therefore, a function of both the characteristics of the incoming signal and our expectations about the signal. The importance of this for the display designer cannot be overstated. Designs that aid the user in maintaining reasonable expectations (based on known facts) will go a long way in preventing errors. Obviously, this strategy ties directly to the notion of creating and supporting good situation awareness.

2.10 Consider Visual Bias

Some displays overlay alphabetical, numeric, symbolic, or some combination of all three types of information onto static or dynamic video. Sometimes this synthetic information is unrelated to the video scene and is just sharing the display space. Other applications present the information with the intention of assisting the viewer in interpreting the scene. In either case, the display designer needs to be aware that the user cannot efficiently process both types of information simultaneously (especially if the scene is dynamic). If the user attends to the scene, changes in the synthetic information may go undetected. The converse is also true. In other words, ecological information seems to be processed differently (or at least separately) from synthetic information. Further, attention cannot be shifted between the two instantaneously—there is a cognitive switch-over time in the hundreds of milliseconds.

Overlaying synthetic information to help the viewer interpret the scene is not always completely successful. In work by Karsh et al (1995) and MacMillan, Entin, and Serfaty (1994), subjects were asked to make detection, classification, or identification decisions about military vehicles seen under varying levels of uncertainty (due to distance, orientation, clutter, or visual noise). Synthetic information was available to aid the subjects in reaching their decisions (e.g., results from a combat identification device, emissive data, etc). In both studies, the subjects overwhelmingly relied on their ability to reach a decision based on their visual sense alone. That is, they either ignored synthetic information about the target, or they did not even request it. The subjects were far more trusting of their own senses and

subjective experience than of information synthesized from other sources. According to Karsh et al (p 17), "seeing is believing." This particular bias may be addressed most effectively through operator training. However, the display designer should be aware of its existence.

3. Specific Topics

Since the discussions on the following specific topics are terse, I have attempted to provide the reader with references to more thorough treatments of the material.

3.1 Absolute Sensitivity to Light

The truly staggering sensitivity of the eye was uniquely illustrated by Pirenne (1948, p 78) with the statement, "The mechanical energy of a pea falling from a height of one inch would, if transformed into luminous energy, be sufficient to give a faint impression of light to every man that ever lived."

The human visual system is not only sensitive to small changes in stimulation intensity (by a factor of 20 or so) but operates across an amazing range of ambient intensity (about 13 log units). The pupil helps to control the amount of light striking the retina (opening in darkness and closing in bright light), but only accounts for about 2 log units of change. Thus most of our ability to detect small changes in intensity across such a wide ambient range is due not to shuttering but to signal processing. In fact, considerable early processing appears to take place at the retina. There are about 150 million rods and cones in the retina, but only about 1 million fibers in the optic nerve, which links the retina to higher order visual centers. This means that data compression at a rate of 150 to 1 occurs before visual information even leaves the eye.

The eyes are most sensitive to light after remaining in the dark for 30 to 40 minutes. Once dark adapted, the most light-sensitive region of the retina lies about 20° away from the central fovea. At this location, the absolute minimum amount of light that is detectable is about 10^{-6} candles per meter squared. Vision at low levels of luminance, known as scotopic, or twilight, vision, is exclusively a function of the rod receptors. As luminance is increased, a point is reached at which the cones become active, and the eye is said to be operating with photopic, or daylight, vision. At this level the perception of color becomes possible, and acuity is improved (most cones are located in the central fovea, where cell density is highest and acuity is best). The change from scotopic to photopic vision takes place at relatively low luminance levels. Beyond about 300 candles per meter squared, no significant improvement in color vision or acuity is noticeable. The eye is not equally sensitive to all frequencies within the visual spectrum. Under photopic conditions, the eye is most sensitive to light occurring at 555 nm (yellow-green). Scotopic sensitivity is best at 505 nm (blue-green). At scotopic

intensities, however, the viewer does not perceive colors—they are sensed as shades of gray.

There are a number of human peculiarities to the way we perceive light. For example, the apparent brightness of a stimulus often has less to do with actual intensity than with the background upon which the stimulus is viewed. Figure 1 shows two large squares, one light and one dark. Inside each square are small circles that are isoluminant (equally bright). Notice that against the darker background the circle appears brighter. This phenomenon (*simultaneous brightness contrast*) is mentioned here only to make the point that human visual perception does not follow the same rules as machine vision. Detailed information regarding the human visual system's response to light can be found in Hood and Finkelstein (1986).

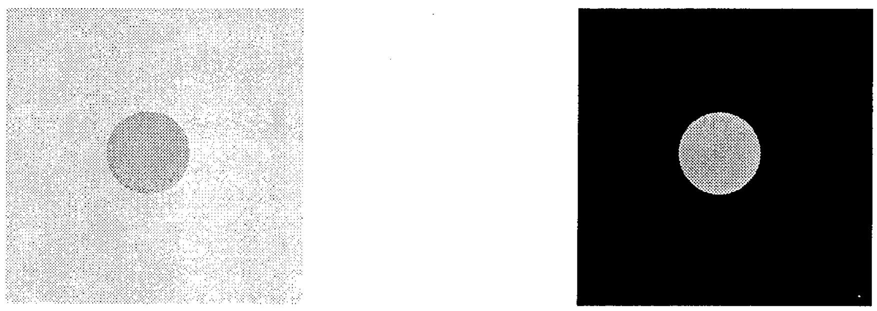
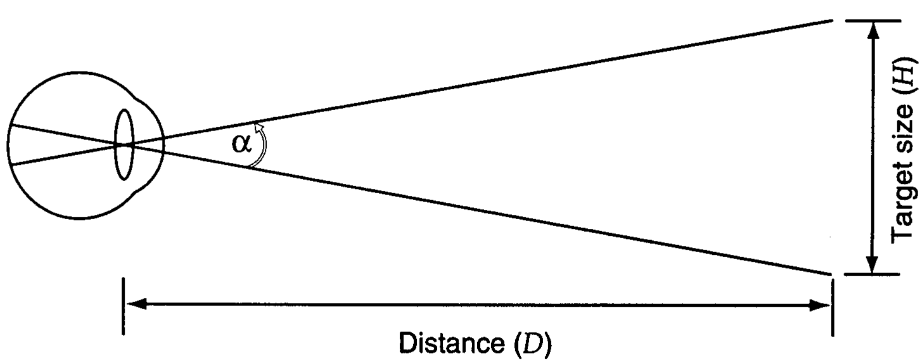


Figure 1. An example of simultaneous brightness contrast showing effect of background on perceived brightness.

3.2 Acuity and the Size of a Display Character

Visual acuity is an expression of the smallest detail that can be resolved by the eye. The size of an object's image, at the retina, is dependent on the physical size of the object and its distance from the viewer. In describing the size of the retinal image, the convention is to use visual angle, since it takes into account both physical size and the distance of the object viewed. Figure 2 gives the most common method for calculating the visual angle. Visual acuity for "normal" observers is about 1 minute (0.29 mrad) of visual angle. This is equivalent to the size of a quarter seen at a distance of 265 ft.



$$\text{ArcTan}\,\frac{H}{D} = \alpha^\circ$$

Figure 2. Method for calculating visual angle of an object of size H at a distance of D.

Acuity is a function of the brightness of the stimulus (more is better), the contrast ratio of the stimulus to its background (more is better), and the retinal location upon which the stimulus image is projected (central fovea is best—at 2° from center, visual acuity is 50 percent of the best possible, and at 12° eccentricity, visual acuity drops to 20 percent of the best possible). For most purposes, a Snellen chart (the standard eye chart found in many ophthalmologists' or optometrists' offices) will provide good estimates of a person's far binocular visual acuity. Snellen acuity ratings refer to the maximum distance at which a person can recognize a letter compared to the distance at which a normal observer can. For example, if a person can identify letters at a distance of 20 ft and normal observers can identify the same letters at 25 ft, then the person is said to have a visual acuity of 20/25.

Department of Defense Handbook 761, *Human Engineering Guidelines for Management Information Systems*, specifies a *minimum* character size of 18 minutes of visual angle. This is a very typical value found in many human factors engineering guidelines for visual displays. This minimum value, of course, assumes that the target background luminance contrast is high (around 94 percent*). It also assumes that the ambient illuminance is typical of an office setting (75 to 100 foot-candles), and that there is no relative movement (e.g., vibration) of the display or the viewer. If the display is emissive (e.g., a cathode ray tube) and is being viewed under direct sunlight, this specification may be insufficient. Motion of the character on the display, or of the viewer relative to the display, will reduce the probability that the character can be correctly identified or discriminated from similar characters. For example, retinal image motion of 15 to 25°/s can reduce visual acuity fivefold.

Considerably more complete information regarding human visual acuity can be found in a chapter on the subject by Olzak and Thomas (1986).

3.3 Alerts

Under certain circumstances, objects on a display can seem to "pop" into the viewer's attention without the viewer having to search for, or fixate, the object. Bestowing this property on an alerting symbol or message has obvious advantages. Flashing an object tends to attract attention. Flash rates of between 3 and 9 per second have been found most effective (Woodson, 1981). This accrues from the rapid changes in the flashing object's luminance. Interestingly, alternating an object's color while keeping the luminance equal will not cause the same effect—thus, the ability of objects to "pop out" is based on abrupt changes in luminance, not color (Theeuwes, 1993).

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*$C = \frac{L - D}{L + D + 2K}$

where C is the luminance contrast, L is the maximum luminance level, D is the minimum luminance level, and K is the luminance from reflected ambient light. All units are in millilamberts.

Where possible, operator alert areas should appear at the bottom of the screen in accordance with research showing enhanced operator reaction times for visual warning signals located in the lower area of the visual field (Boff and Lincoln, 1988). Adding an auditory component will also significantly improve the probability that an operator will attend to an alert.

3.4 Binocular Rivalry

Binocular rivalry is a phenomenon often associated with the use of monocular displays. It is characterized by a temporary loss of sight in one eye for periods of two or more seconds. This "blindness" is so compelling that users report an initial tendency to attribute it to the eye being closed. One user, a helicopter pilot, described this temporary blindness as "at least two seconds of pure terror."

The etiology of binocular rivalry involves presenting disparate views to the eyes (dichoptic viewing). Normally, an object viewed binocularly casts similar images on corresponding points of both retinas. In the brain, this information is combined to yield a single, stable perception of the object at some distance from the observer. However, when the eyes receive disparate stimulation, sending contradictory information to the brain, the fusing of the two monocular signals can become impossible. The brain reacts to this circumstance by suppressing the information from one eye while allowing the information from the other eye to be processed. Because both eyes are competing for conscious attention, the right eye's view will be seen for a period of time and then will disappear in favor of the left eye's view. These alternations cannot be influenced by conscious effort and will continue for as long as the observer views the rivaling stimuli. Rivalry has been induced with differences in luminance (Sherrington, 1911), color (Triesman, 1962), spatial frequency (Blakemore, 1970), orientation (Kertesz and Jones, 1970; Braddick, 1979), direction of motion (Wade, de Weert, and Swanson, 1984), and velocity (Blake, Zimba, and Williams, 1985). A difference in luminance between the two eyes, however, seems to be the most powerful agent in causing rivalry. The eye receiving the least luminance will experience the most suppression.

Of principal concern to the designer of monocular displays is the fact that information presented to the suppressed eye will not be perceived. Given a description of the views presented to each eye (luminance, spatial frequency, etc), the rate at which suppression will occur and the duration of suppression can be estimated. However, it is extremely difficult (probably impossible) to predict *when* vision from either eye will be suppressed. Clearly, this is not a trivial problem, and the designer working with monocular display systems would be well advised to investigate the binocular rivalry phenomenon in more depth.

3.5 Blind Spot

There is an area on the retina that contains no photoreceptors and is, thus, completely insensitive to light. Called the optic disk, or blind spot, this is

the point where blood vessels enter the eye, and the optic nerve exits. The blind spot is approximately 5° across, is circular, and lies along the horizontal meridian 15° out from the retina on the nasal side. The resulting loss of visual information is usually not noticeable because of the overlapping fields in binocular vision. In other words, that portion of the visual world that is invisible to the right eye, because of the blind spot, is sensed by the left eye, and vice versa. If a display is going to be viewed monocularly, however, information projected onto the blind spot will not be detected.

3.6 Color

The fact is, people like color. No one watches black and white television any longer, and no one wants to use a black and white computer monitor, either. Color displays are esthetically pleasing (usually) and more visually interesting than achromatic displays. Most people also report that their performance is better when using a color display compared to an achromatic display. Often this opinion has no basis in fact. Even so, the perception of enhanced performance (fact or not) is desirable and, by itself, forms one argument for the use of color.

The perception of color probably exists because it provides us with another stimulus dimension that we can use to discriminate between objects in the visual world. The physical energy that we call "light" has no color. Color is manufactured in the visual system as a result of our differential sensitivity to the wavelength of the electromagnetic energy. If the wavelength falls in the visual spectrum (380 to about 760 nm) we perceive hues from violet through blue, green, yellow, and orange, to red. The perceptual experience of color is multidimensional, composed of the qualities of hue, saturation, and brightness. *Hue* is the psychological dimension that most closely corresponds to the signal's wavelength. *Saturation* refers to the purity of a color; if white light is mixed with a pure spectral hue, the color seems to become washed out, or less pure (and thus less saturated). *Brightness* is our subjective impression of a light's intensity.

Interestingly, brightness does not share a linear relationship with the amount of light incident on the retina (retinal illuminance). If one were to plot the apparent brightness against retinal illuminance, the brightness would increase approximately as the cube root of the energy. For example, to double the apparent brightness of a light requires an eightfold increase in luminance. If this were not confusing enough, the apparent brightness also varies by wavelength (or hue). Red, when viewed in the daylight, appears much brighter than blue. As illumination decreases, however, the blue stimulus will seem to brighten while the red stimulus darkens. This interaction among illumination, wavelength (hue), and apparent brightness is known as the Purkinge shift and is a good example of how uniformly varying a physical stimulus dimension, like intensity, can result in nonlinear perceptions.

On the other hand, some glaring changes in the dimension of a physical stimulus (size, color, etc) can have absolutely no accompanying change in

perception. For example, suppose you see a coworker wearing a red shirt in a room illuminated with a tungsten light. If you then see the person in another room, illuminated with fluorescent light, you do not think he has changed shirts even though the photometric characteristics of the two retinal images are very different—because of the differences in spectral radiance between the two light sources. When someone walks away from you, you do not perceive that person as getting shorter, even though that is what the information at the retina is indicating. Similarly, a doorway viewed at an angle still seems to be a rectangle, even though the image at the retina is not.

This difference between retinal image and conscious experience points to the fact that what we see is really an *interpretation* of the stimulus world. Our visual system is constantly trying to create a world that is perceived as stable by employing strategies called the *visual constancies*. These processes unconsciously affect our perception of size, color, shape, distance, brightness, position, and direction. In short, there is nothing simple about the way people perceive color, or anything else in the visual world.

For the display designer, color exhibits its greatest advantage in grouping like objects. Coding with color enables the viewer to perform a global search for all objects of the same color. This is apparently a parallel search that is performed on all stimulus elements simultaneously, as opposed to a feature by feature serial analysis. Thus, color codes can result in higher detection accuracy and search times that are 50 to 70 percent faster than other codes (Smith and Thomas, 1964). The use of color as a redundant code also improves visual search performance. For example, a tactical display may use diamonds to represent enemies and circles to represent friends. Thus threat class is coded by shape. If all diamonds are one color and all circles are another, then threat class is redundantly coded. One caution, however: if color is used as an irrelevant code, search performance is degraded (Christ, 1975).

How many colors should be used on an information display? It is estimated that the number of colors (either reflected from a surface or generated by a luminous display) that can be discriminated exceeds seven million. This assumes that the comparison is relative, not absolute. No one, however, recommends using that many colors for coding information. Most researchers recommend using no more than six or seven colors in an information display (Carter and Cahill, 1979). Map displays, however, often require more than a few colors. One suggestion for map displays is to use 10 basic hues, varying each with two levels of saturation and three levels of brightness. This yields 60 possible combinations, which should be easily discriminable. DeCorte (1988) has developed an algorithm for picking display colors that exhibits a more or less uniform separation in perceptual color space. One problem with the algorithm is that it cannot consider the color's appearance (i.e., you cannot specify that one of the colors looks like red).

Not surprisingly, there are caveats in the use of color. Display designers should know that slightly more than 8 percent of North American and Eu-

ropean males (and 0.05 percent of females) have some form of color blindness (Coren et al, 1984). The most common form of color anomaly is called deuteranopia, in which the individual has a malfunction in the green cone system. Consequently, relying on color as a display character's only coding dimension invites errors from this segment of the population.

Designers should also be aware of many stereotypes concerning the use of color. For example, from automobile driving we learn that red commonly indicates stop or danger, yet red is often used to indicate power on for electrical or electronic systems. Problems can also arise from color pairings. If saturated red and blue appear in close temporal and spatial proximity, it can be very difficult for the user to extract information from the display. The worst case is when blue is used as a background color for red text or symbology, or vice versa. Red and blue exist at the opposite ends of the visible spectrum and, when used together, can cause an inability for the eye to focus both colors simultaneously, because of the nonlinear refractive index of the lens. Blue objects or text may appear to move away from and red elements to move toward the viewer, creating a three-dimensional effect called chromo-stereopsis. For some viewers, even relatively short exposure to such displays will cause asthenopia, a fatiguing of the eyes causing discomfort, dimness of vision, and headache. Low color contrast can also be problematic (i.e., yellow alphanumerics on a white background).

As mentioned earlier, hue and intensity interact in less than intuitive ways. For example, prolonged viewing of a very bright spectral red (630 nm or so) will cause it to take on a yellow, and sometimes even a green, hue. This phenomenon is known as the Bezold-Brucke effect. Needless to say, confusion among red, yellow, and green on a display device could have serious repercussions. More important is the fact that *color masks luminance*. In other words, people can easily judge the relative brightness difference between two achromatic stimuli but cannot do the same if the stimuli are colored. Consequently, the user must never be required to discriminate brightness differences between two colored display elements. Interestingly, the perception of motion is driven by brightness contrast, with color being unimportant. That is, if the brightness is identical between a target and its background (their only difference being color) and the target is moving, the perception of target motion will be misleading in two aspects. First, the target motion will be perceived as slower than it actually is, and second, the movement will not be seen as smooth. Thus, maintaining a difference in brightness between target and background will aid the viewer in correctly perceiving target motion.

The size of a stimulus, its color, and its shape interact in several interesting ways. For example, imagine that a display designer is creating a visual display to be used in a tank simulator. The display will be computer driven and will simulate the view out of a tank's main gun sight. Because of constraints on computational power, it has been decided to use the same shape for representing both friendly and enemy tanks, but enemy tanks will be brown, and friendly tanks will be green. The designer wants the soldier using the simulated gun sight to be able to identify enemy tanks at

ranges that are similar to those observed in the field with real tanks. However, he finds that soldiers using the simulator can regularly identify enemy tanks at three or four times the distance possible in the field. What has gone wrong? The error is in using color rather than shape as the determining feature of target identification. In the field, visual target identification is made based on the shape of the target (including both low and high spatial frequency elements). In the simulator, however, a distant enemy tank first shows up on the display as only a few brown pixels. A few pixels cannot provide enough information to represent shape, but once the soldier notices that the pixels are brown, the target's identity is no longer in doubt. In other words, for very small targets on emissive displays, color can be discriminated when shape cannot.

When stimuli are small, discriminating between some colors becomes difficult (especially in the higher frequency portion of the visible spectrum). Specifically, if stimulus size drops below 2° of visual angle, yellow-blue discrimination deteriorates more quickly than red-green discrimination—a phenomenon commonly referred to as *small-field tritanopia,* because the viewer's experience is analogous to that of a person who is deficient in blue sensitive cones. This is noteworthy if the display designer will be showing small blue and green symbols to the viewer, and the ability to discriminate between the two colors is important.

The reader wishing further information about color vision is referred to Pokorny and Smith (1986) and Graham and Hsia (1958). For more information on the use of color in electronic displays, see a report by the North Atlantic Treaty Organization (1990) and Schneiderman (1987).

3.7 Eye Movements

The large ballistic movement of the eyes from one point of gaze to another is called a saccade. Saccadic eye movements can reach velocities of up to 800°/s and can occur as frequently as three or four times per second (Moray, 1969). During a saccade, the retinal image is blurred as the visual world wipes quickly across the back of the eye. Even so, the information is dutifully sensed by the retina and transmitted to higher visual centers in the brain. However, the information never reaches consciousness. That is, you will continue to see whatever you were looking at, just before the saccade, until the eyes have completed their move. Then you will see the new scene.

The ability of the brain to suppress vision, during a saccade, is something most people are not aware of. You can experience this phenomenon quite easily for yourself. With a friend watching over your shoulder, look into a mirror located about 16 inches in front of you. Look first at the image of your right eye in the mirror. Then look at the image of your left eye. Keep switching your point of gaze between the two. Notice that you cannot see your eyes move. You may be able to *feel* them move, but you cannot *see* them move. Your friend will, of course, see your eyes move back and forth.

Why does the brain suppress visual information during a saccade? The answer is probably because it provides no useful information. Economy of processing seems to be the principle. Incoming sensory data are nearly unlimited, but processing capacity is quite limited; the brain must therefore strive to allocate processing resources to the most salient elements of the environment. In the case of the saccade, sensory data from the proprioceptive and motor systems and from the extraocular muscles combine to tell the brain that the rapid wiping of the visual image across the retina is due to eye movement alone and not to the movement of the world (which would be important information) or to movement of the head or body (also important).

This phenomenon is important to the display designer, because information that appears, disappears, or changes while the viewer's eyes are making a saccadic movement will not be perceived. In order for these changes to be noticed, the viewer will have to look directly at the location where the change occurred and compare what is currently there with what is remembered about that location from the last time it was viewed. This often takes the form of an element-by-element serial search, which is painfully slow and relies heavily on the user's short-term memory—an error-prone situation at best. Thus, adopting a method to insure that the user notices important display changes is desirable. One method is to cause the new information to flash for 1 or 2 s. This can be combined with a change in color or brightness to maximize the probability that the viewer will notice the change. The method selected should be unique to its purpose, so as to avoid confusion with other alerts.

Additional information is available in a series of books from symposia on eye movements (Monty and Senders, 1976; Senders, Fisher, and Monty, 1978; Fisher, Monty, and Senders, 1981; Groner et al, 1983).

3.8 Flicker

The temporal contrast sensitivity of the eye varies according to a number of factors, such as the size of the stimulus, its retinal location, the shape of the waveform, and the ratio of on-time to off-time. However, if the concern is flicker resulting from screen refresh rate, the most relevant factor is probably the average display luminance. The greatest frequency at which flicker can be perceived increases linearly with the logarithm of the average luminance. Thus a tenfold increase in average luminance will add 10 Hz to the highest frequency at which display flicker can be detected. There are some subtle implications here. A display using positive contrast (light characters on a dark background) shows a typical background luminance of about 1 mL, a character luminance of about 25 mL, and an average luminance of about 6 mL (with a character density of 30 percent). The same display using negative contrast (dark characters on a light background) typically has a background luminance of 25 mL, a character luminance of 1 mL, and an average luminance of 16 mL. Clearly a display using negative contrast will be perceived to flicker at much higher refresh rates than one using positive contrast. Faced with a display that suffers from a low re-

fresh rate, the designer can reduce the potential for flicker by employing methods to lower the average luminance (including using positive contrast). The trade-off, of course, is that average luminance levels that are too low can negatively impact foveal vision.

3.9 Foveal Versus Peripheral Vision

The human eye is continually sampling both a large segment of the visual world (the peripheral field) and a very much smaller segment (the foveal field). Both analyses are conducted in parallel. A very cursory look at the organization of the visual system is helpful in exploring the advantages and disadvantages offered by foveal and peripheral vision.

The human visual system is known to be made up of a number of specialized, parallel information channels. The two channels of principal interest here are the *parvocellular* and *magnocellular* channels. The parvocellular channel originates within the fovea and is characterized by small receptive fields (providing good acuity) and sustained responses. These small receptive fields require tiny axons, which result in long conduction times to higher visual centers. This channel also has a relatively long integration time, with a peak temporal modulation transfer function (MTF) of 10 Hz. It is most sensitive to high spatial frequencies, has comparatively low contrast sensitivity (cannot detect faint images), and is sensitive to color.

In contrast, the magnocellular channel sums responses over large areas (poor acuity) and is thus highly sensitive with good temporal response. Originating in the periphery, magnocellular elements feed large neurons, with short conduction times to higher centers, and respond phasically, providing transients at stimulus onset and offset. The magnocellular system has a much shorter integration time (temporal MTF of 20 Hz), has a preference for low spatial frequencies, and is highly contrast sensitive (can detect faint images). Because the magnocellular channel is sensitive to a broad band of spectral frequencies, it is essentially color-blind.

Obviously, when color perception or the resolution of high spatial frequencies is required (as in reading), information must be presented to the fovea. However, peripheral vision is often overlooked as an appropriate information channel, even though it is superior to foveal vision in absolute sensitivity to light and in the perception of self-motion, or vection. The reflexive nature of peripheral field spatial orientation points to the automatic processing of this type of information (Walrath, 1994). This is particularly important when viewed in terms of the design of visual displays for aiming, guidance, and navigation through real or virtual environments. According to Leibowitz (1986, p 605), "Although many spatial orientation functions could be carried out with central vision, it is functionally more efficient to utilize the peripheral fields for spatial orientation so as to free central vision for those tasks for which it is uniquely specialized."

Several aircraft display systems have been created for the peripheral visual field. Both the para-visual director and the peripheral command indicator

take advantage of the peripheral field's sensitivity to changes in luminance. They use variations on a rotating "barber's pole" to create a luminance rate field that signals the pilot to rates of change in aircraft orientation or glide path. Another display designed for use with the peripheral visual field, the Malcom horizon, projects a laser-generated line across the instrument panel. The line remains parallel to the horizon, thus indicating the aircraft's relative position with respect to level flight. This horizon line can be easily monitored via peripheral vision while central vision is used for other tasks (Malcom, 1984).

Further information can be found in the work of Anstis (1986) and Carr (1986).

3.10 Reaction Time to Visual Stimuli

Normally, a user can respond to a single visual event, like the onset of a light, in 200 to 300 ms. In order to achieve this reaction time, the user must know that the stimulus is going to appear (but not necessarily when), where it will appear, and what the correct response to the stimulus is. More complex visual events can require cognitive processes that yield reaction times in the minutes (Meister, 1985).

A related topic is that of temporal integration time. The temporal integration time for human vision is about 100 ms, meaning that two visual events that occur no more than 100 ms from each other will be perceived as having happened simultaneously.

3.11 Reading Text

Whenever text is displayed (in menus or as information elements), the use of lower case letters, where reasonable, is desirable. This guideline is based on the fact that lower case letters provide information, to those cognitive elements responsible for word recognition, not available with upper case text. Words can be discriminated from one another by means other than a comparison of their letters. The shape of a word has been identified as a powerful perceptual cue (Haber and Schindler, 1981; Healy, 1976). Lower case letters contain full-line ascending and descending characters (e.g., *d* and *g*, respectively) as well as half-line characters (e.g., *u*, *a*, and *e*). Combining these different elements into a word creates a global pattern that can be recognized. Consequently, lower case words are often recognized by their shape (global element recognition) rather than by an individual analysis of letters (local element recognition). Frequently encountered words are especially prone to global recognition (Corcoran and Weening, 1967). Obviously, as the user's experience with the display increases, the frequency of exposure to the domain semantics will also increase. It follows, then, that the degree to which frequently used words are susceptible to global recognition will increase.

Aside from supporting word recognition by adding a secondary source of information, global perception of visual information is processed differ-

ently from local detail. First, it appears that global perception precedes feature-by-feature analysis (Reicher, 1969; Wheeler, 1970; and Navon, 1977). Second, research indicates that global perception is a preliminary, preattentive, wholesale analysis that is performed without conscious control—and is therefore a parallel (automatic) process (Neisser, 1967; Cooper, 1974). Simply put, the shape of a word is available for processing before the information offered by the individual letters, and processing is accomplished without recourse to controlled processes, diminishing cognitive workload.

3.12 Redundancy Gain

Often, the display designer will want to insure the maximum probability that a critical information element can be discriminated from other elements and identified correctly. Using more than one coding dimension (e.g., both shape and color) to represent a single information dimension (e.g., threat class of a target vehicle) will provide a performance advantage greater than can be achieved with either dimension separately.

3.13 Stress

Stress affects human performance in a number of ways. Most relevant here, however, is a phenomenon known as *perceptual narrowing*. Imagine that your attention to the outside world is like the beam from a spotlight. You attend to sights, sounds, smells, etc, that are illuminated by the spotlight, while those elements of the environment that lie outside the spotlight are not in your consciousness. In times of stress, the diameter of the spotlight's beam can shrink appreciably. According to Schmidt (1989), "This is usually thought of as a reduction in the ability to deal effectively with relatively unlikely peripheral events in favor of focusing on more likely central events." The importance of this for the display designer is that users, under stress, will often *not* see or hear critical information that, under more relaxed circumstances, would be seen or heard. Overcoming this shrunken perceptual field phenomenon is not a trivial problem. Forcing all critical information to the user's central attentional field usually cannot be done, because of a lack of physical display space. Even predicting where a stressed user's central attentional field will be is problematic. Being aware of the phenomenon at least forewarns the designer and may result in some display modifications addressing the stressed operator. Further information on the effects of stress on decision making can be found in Wright (1974), Tversky and Kahneman (1974), and Einhorn and Hogarth (1981).

4. Conclusion

Information and knowledge are not synonymous. In designing visual displays, the goal is not simply to provide information but to impart knowledge. One method the display designer can use to address this requirement is to ask a series of questions, and time spent in their thoughtful analysis will prove to be an excellent investment. The first question is, "What knowledge does the user need to successfully perform his/her mission?" The next question is, "What information must the user have in order to acquire the requisite knowledge (and, conversely, what information is irrelevant)?" Finally, the display designer must ask, "What is the most effective way to display this information so that it becomes knowledge with a minimum of user effort?" The degree of success achieved by any display design will hinge on the mastery of these three issues.

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